LA-UR 94-3400

CONF-9409245--

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE "High Magnetic Fields in the USA"

AUTHOR(S): Laurence J. Campbell, Jack E. Crow,
Don M. Parkin, Hans J. Schneider
Neil S. Sullivan

SUBMITTED TO: Second European Workshop on Science in 100
Tesla, Leuven, Belgium
September 30 - October 1, 1994

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

MASTER

HIGH MAGNETIC FIELDS IN THE USA

L. J. Campbell[a], J. E. Crow[b], D. M. Parkin[a], H. J. Schneider-Muntau[b], N. S. Sullivan[c]

[a]National High Magnetic Field Laboratory
Los Alamos National Laboratory, MS-K765
Los Alamos, NM 87545, USA

[b]National High Magnetic Field Laboratory
Florida State University, 1800 East Paul Dirac Drive
Tallahassee, FL 32306-4005, USA

[c]Department of Physics
University of Florida
Gainesville, FL 32611, USA

I. Introduction

During the past thirty years research using high magnetic fields has technically evolved in the manner, but not the magnitude, of the so-called big science areas of particle physics, plasma physics, neutron scattering, synchrotron light scattering, and astronomy. Starting from the laboratories of individual researchers it moved to a few larger universities, then to centralized national facilities with research and maintenance staffs, and, finally, to joint international ventures to build unique facilities, as illustrated by the subject of this conference.

To better understand the nature of this type of research and its societal justification it is helpful to compare it, in general terms, with the aforementioned big-science fields.

High magnetic field research differs from particle physics, plasma physics, and astronomy in three respects:

1. It is generic research that cuts across a wide range of scientific disciplines in physics, chemistry, biology, medicine, and engineering.

2. It studies materials and processes that are relevant for a variety of technological applications and it gives insight into biological processes.

3. It has produced, at least, comparably significant results with incomparably smaller resources.

Unlike neutron and synchrotron light scattering, which *probe* matter, high magnetic fields *change the thermodynamic state* of matter. This change of state is fundamental and independent of other state variables, such as pressure and temperature. After the magnetic field is applied, various techniques are then used to study the new state.

In the United States the National Science Foundation (NSF) has major responsibility to support high magnetic field research. In 1971 the transition to a centralized national facility mentioned above was further confirmed when the NSF assumed primary support for the Francis Bitter National Magnet Laboratory (FBNML) at MIT, which had been established in 1960 with the support of the U. S. Air Force Office of Scientific Research. The need for such a national center was amply justified by the number of users, which in 1990-1991, for example, was 348, from all over the world.

By 1978, significant high field facilities were in place, not only at FBNML, the Naval Research Laboratory, the University of Pennsylvania, and the University of California at Berkeley, but at several centers throughout Europe and Japan. The National Research Council deemed it timely to consider where the development of high field technology was going, and what importance this had for research and technology. This led to the report of the Panel on High Magnetic Field Research and Facilities (1979), chaired by S. P. Keller of IBM, which listed a number of major research opportunities and technological objectives. Among its chief recommendations, "The design and construction of a quasi-static pulse magnet with fields approaching 100 T should be undertaken." [1]

In 1987 the NSF convened a Panel on Large Magnetic Fields, co-chaired by F. Seitz of the Rockefeller Foundation and R. C. Richardson of Cornell University, to assess future scientific, engineering, and technological opportunities in high magnetic field research. The panel was unequivocal in its findings. Not only had such research "been extraordinarily productive for modern advances in our knowledge of physics, chemistry, materials engineering, and biology," but there were "remarkable opportunities for the discovery of new states of matter..." and for "important applications in technology such as new devices for the computer industry, new materials with exceptional strengths and major advances in medicine." The principal recommendation of the Panel was the establishment of a new National High Magnetic Field Laboratory (NHMFL). [2]

This occurred in 1990 through the formation of a unique federal-state partnership supporting a consortium of two universities (Florida State University and the University of Florida) and a national laboratory (Los Alamos), with primary support from the NSF and major start-up support and substantial continuing support from the State of Florida. [3]

The *sine-qua-non* of generating high quasi-static fields is a power source that can provide hundreds of megawatts. Such a power source is available at Los Alamos in the form of a 1.4 GW synchronous motor-generator which is configured to provide energy pulses of 600 MJ within approximately 1 second. This national resource was the primary factor driving the establishment of the Florida-Los Alamos consortium which operates the NHMFL. As a contingency, provision has been made for the addition of a flywheel, which could more than triple the energy output. [4] Consequently, the main component of the NHMFL-Los Alamos program is a 60 T, 100 ms quasi-static magnet with 32 mm bore that will use this generator (without a flywheel). [5] Moreover, the 60 T magnet has the full pulse-shaping capability that is made possible by the ac power output of the generator, in a manner similar to the 40 T quasi-static magnet at the University of Amsterdam. [6] For the future, this motor-generator is the backbone of the 100 T, 20-50 ms project that will be proposed for the next NSF funding cycle and of future facility concepts that would extend the 100 T field to pulse durations on the order of 1 second. [7]

II. Francis Bitter National Magnet Laboratory

We concentrate in this paper on the NHMFL, both because one of its future program objectives dovetails with this conference [4] and because future high magnetic field research will concentrate there. However, it is important to recognize the extensive facilities in place at FBNML, not to mention the major contributions to magnet technology and the many outstanding research accomplishments FBNML may justly claim. Also, the long experience of FBNML as a user facility has honed the expeditious and knowledgeable support that users now consider standard.

The magnets at FBNML are summarized in Table I.

Table I — FBNML Magnets

Power (MW)	Max. Field (T)	Bore Size (mm)	Characteristics	Quantity
9	35	33	Hybrid Solenoid	1
9	31.5	32	Hybrid Solenoid	1
9	27	51	Hybrid Solenoid	1
9	23	144	Hybrid Solenoid	1
9	24	32	Solenoid	4
9	20	51	Solenoid	5
5	19.5	32	Solenoid	3
5	15.5	51	Solenoid	5
5	14.5	51	Uniform Field Solenoid	1
9	17	20 mm gap	Radial Access, H gap	1
9	15	32 mm gap	Radial Access, V gap	1
5	11	20 mm gap	Radial Access, H gap	2
5	10	32 mm gap	Radial Access, V gap	1
5	8	51 mm gap	Radial Access, V gap	1
8	14.5	102	Large Bore Solenoid	2
8	12.5	147	Large Bore Solenoid	1
8	7.5	248	Large Bore Solenoid	1
-	15	51	Supercond. Solenoid	1

In addition to the above magnets, FBNML has offered pulsed fields on an experimental basis and has achieved record fields as part of its pulsed field development.

The 45 T hybrid magnet of NHMFL is being built through a collaboration between design teams from FBNML and NHMFL, with primary responsibility for the resistive insert and the NbTi coils of the superconducting outer magnet being assigned to FBNML. [8]

III. NHMFL: Objectives and Capabilities

The NHMFL has made its first step in advancing both the state of the art in magnet design and technology and in the exploration of new scientific phenomena. The facility provides not only the opportunity to carry out experiments at the highest attainable fields (currently, up to 27 T with continuous resistive magnets, 60 T for capacitor-driven pulsed magnets, and in 1995, 45 T with the hybrid magnet) but the quality of the power installations and magnet performance has been advanced to meet the needs of high sensitivity and the requirements of electrical noise and mechanical vibration reduction that are crucial to many modern experiments. As examples of this emphasis on quality we can cite the recent observations of solid state NMR in the 27 T magnets and the measurements of magneto-oscillatory behavior in the 60 T capacitor-driven pulsed magnets. These phenomena cannot be observed without great attention to stability and the elimination of electromagnetic noise and vibration.

The combined emphasis on building magnets, with user friendly characteristics (volume, control, stability, access, etc.) at field levels much higher than currently available, and the development of the appropriate scientific infrastructure, including new instrumentation and measuring techniques, will set new milestones and standards. This emphasis defines NHMFL's mission as we enter the second phase of the project after completion of the first five year's program with the NSF.

One of the unique features of the new national magnetic field laboratory is the extension to research and the use of magnet technology in the health sciences and biophysical phenomena. NHMFL is in collaboration with the Brain Institute at the University of Florida developing a major effort to use Magnetic Resonance Imaging (MRI) techniques for practical applications such as in the repair of spinal cord tissues. The laboratory plans to assemble a 12 T, 40 cm diameter imaging magnet for studying *in-vivo* small animals to develop advanced techniques in this and related fields. This will be the world's largest MRI magnet.

The Institute for Advanced Studies of Magnetic Resonance and NMR magnets

A prime and unique feature of the magnetic resonance program is its large-scale integration of NMR, MRI, EPR, and ICR spectroscopies, which have many common conceptual and technical aspects. Among the instruments that are and will be housed in the specially designed NMR Laboratory are the 'flagship' 900 MHz NMR spectrometer, an 850 MHz spectrometer for solid state,a 720 MHz spectrometer, a 600 Mhz wide-bore spectrometer for micro-imaging, a 500 Mhz standard-bore spectrometer for biomolecular NMR, a 300 MHz wide-bore spectrometer for development of solid-state methods, and a 300 MHz standard-bore spectrometer for solution state methodology.

In addition to projects now under way, further research will be concerned with the development of technology that is relevant to very high magnetic fields, such as probes and receiver systems, magnetic resonance using non-persistnet suerconducting, resistive, and pulsed magnets, similarities of NMR and ICR in multidimensional methods, and development of multiple-resonance methods.

Ultra-High B/T Facility

In addition to providing facilities for studying new phenomena at the very highest magnetic fields, the National High Magnetic Field Laboratory is also developing a unique facility to carry out experiments at the highest fields and lowest temperatures simultaneously. Several interesting new phenomena such as new states of nuclear spin ordering and magneto-thermodynamic transport in highly polarized quantum fluids can be or are predicted to be realized by the establishment of very high initial magnetizations or high spin polarizations, achieved by a high ratio of the applied magnetic field to the temperature B/T.

Examples of new phenomena that can be explored by an ultra-high B/T capability include the transport properties of highly polarized fluids. A number of unusual magneto-kinetic effects are predicted for spin transport in highly polarized Fermi fluids. High field broadline NMR studies can be used to study the predicted instabilities in the ground state of alkali metals due to strong exchange and correlation effects that could lead to charge density wave formation. New states of nuclear magnetism can be examined because of the ability to lower the nuclear spin entropy below critical values by static cooling in the high initial B/T conditions. Specifically, the upper critical field for the nuclear spin order/disorder transition in solid helium three can be determined for the first time at very low temperatures.

The facility is being developed in collaboration with the Microkelvin Research Laboratory at the University of Florida and will consist of a complex two-magnet system. An 8 T nuclear demagnetization stage will be used to cool samples to 500 microkelvin (or below). The experimental region is in the center of an 18 T persistent superconducting magnet and the complete system is located in an ultra-quiet environment with "tempest" quality shielding from radiofrequency interference and noise, and also with special vibration isolation.

Resistive magnets

NHMFL is pursuing an aggressive program to extend the state-of-the-art of the quality and magnitude of resistive magnet fields. (A summary of this program is given in Table II.) The present development focuses on magnets which use only two of the four 10 MW power supplies, allowing 2 magnets to be run in parallel. Currently available field levels of 27 T will be increased with the addition of a 30 T system by the end of 1994 and a 33/34 T system in the summer of 1995. The attention to quality is illustrated by the 27 T magnets recently put into service, which permit broadline NMR.

A number of especially interesting properties of new materials that exhibit new behaviors at very high magnetic fields can be studied by using broad-line NMR techniques for only moderate homogeneities. The very high quality of the power systems for the water cooled resistive magnets and the quite good homogeneities of the new NHMFL design for the 27 T class magnets will allow these broad-line NMR experiments to be carried out. Test cases to observe NMR in these magnets have already been successful, and with some modest improvements in homogeneity with small added correction coils a number of NMR experimental techniques will be accessible.

This ability has drawn considerable user interest and examples of current interest include the examination of field induced transitions and the effects of dimensional instabilities in the organic superconductors for which NMR can follow the local fields directly and provide insight into the magnetic correlations. Spin density wave motions and their excitation energies can be determined from NMR line narrowing measurements. The correlation effects and anisotropies of materials that exhibit high temperature superconductivity can be explored in very high fields to yield information about the magnetic phases in some of these materials and probe the interplay between bonding and exchange interactions in the highly correlated materials. The sublattice magnetizations in the magnetic phases can be deduced from measurements of the line structure resulting from the hyperfine interaction and explored in detail for single crystals. A comparable scientific potential stemming from field quality will be realized also in the hybrid, described below.

Hybrid magnet

The highest steady fields available anywhere in the world will be provided by the NHMFL 45 T Hybrid. [8] Owing to the physical size and inductance of its superconducting outsert, the field uniformity and stability in the 45 T hybrid will also be significantly improved relative to the resistive magnets. The system is designed for maximum availability (the outsert can be charged or discharged in less than 1 hour), reliability (the outsert is stable even against an insert trip), and ease and economy of operation (the outsert is connected to a dedicated closed-cycle refrigeration system), making its utility the virtual equal of the resistive systems for many applications and the superior system where higher fields are essential.

The NHMFL Hybrid is designed to provide the full 45 T rated field routinely – not just as a record achieved once during proof tests. Its standard bore of 32 mm is the same as the resistive systems and the 60 T quasi-static magnet. However, future inserts can provide larger bores at reduced fields if warranted. In addition, the superconducting outsert will be available by itself for technology applications, providing fields in excess of 15 T over its 616 mm warm bore (approximately 16.5 T maximum at the midplane).

Pulsed magnets

The highest pulsed fields at Los Alamos are produced by explosive flux compression generators which reach 100 - 200 T in 11 - 16 mm bores for a few µs. NHMFL users have measured de Haas - van Alphen frequencies and upper critical fields of high temperature superconductors with this technique, but the sacrifice of the sample is an unpopular feature. In a recent collaboration between Los Alamos and scientists from Arzamas-16, Russia, fields in the vicinity of 1000 T were obtained. There can be opportunities for NHMFL users to add experiments to such scheduled events.

Now used in many laboratories throughout the world are pulsed field magnets driven by capacitor banks that produce fields in the vicinity of 40 to 60 T for about 20 ms in bores ranging from 10 to 24 mm. At NHMFL the working field is chosen to be about 8 T less than that which destroyed an identically fabricated magnet. However, this down-rating merely postpones eventual failure which is a result of fatigue and wear after a few hundred pulses, but is usually not catastrophic. Various designs have been successful for this class of magnet. NHMFL uses the design developed at Leuven, which employs graded thicknesses of fiber reinforcement between conductor layers.

The principal near-term pulsed magnet for NHMFL is the 60 T quasi-static, controlled pulse magnet which is now nearing completion. Similar magnets are under development at the University of Amsterdam and Princeton University, although the latter will not have the controlled pulse feature. This magnet, whose forerunner in concept is the highly successful 40 T quasi-static magnet at the University of Amsterdam, will offer a wide variety of pulse shapes, including flat-tops, steps, ramps, field reversals, and crowbars, over periods ranging from 100 ms (for the 60 T flat-top) to several seconds (for a crowbar decay). The success of its multi-coil design is highly relevant to the NHMFL 100 T nondestructive magnet. In particular, the outer coils of the 100 T magnet are quite similar to those of the 60 T quasi-static magnet.

Summary of Magnets at NHMFL

The magnets now available and scheduled for completion (with the exception of the 900 MHz NMR magnet) during the first phase of NHMFL are summarized in Table II, roughly in order of completion. The specialized flux compression generators are not listed.

Table II — NHMFL Magnets for Period 1991 - 1995

Power (MW)	Max. Field (T)	Bore Size (mm)	Characteristics	Quantity
-	20	52	Supercond. Solenoid	3
-	50	24	Pulsed, capacitor	1 - 3
-	60	16	Pulsed, capacitor	1 - 3
8	20	50	Solenoid	2
-	20	52/31	Solid state NMR	1
13	27	31	Solenoid	3
-	720 MHz	52	High resolution NMR	1
15	30	32	Solenoid	1
-	600 MHz	89	High resolution NMR	1
-	500 Mhz	52	High resolution NMR	1
-	18	50	High B/T, 400 μK	1
300	60	32	Pulsed, quasi-static	1
24	45	32	Hybrid	1
12	25	50	Solenoid	1
20	32	32	Solenoid	1
-	900 MHz	110	High resolution NMR	1 (1997)

IV. NHMFL: Objectives for 1996-2000

It should be recognized that important components of high magnetic field research do not always use the very highest attainable fields. An example within NHMFL is fourier transform ion cyclotron resonance mass spectrometry (FT-ICR), which already offers impressive performance at 7 T (the highest field presently in use) such as the detection of a single DNA ion of 100,000,000 Dalton molecular weight and the mass resolving power sufficient to distinguish thousands of components in a mixture as complex as crude oil. Suffice to say that magnets of higher field and larger bore sizes are on order or in the process of proposal that will advance the capabilities of ICR on all fronts; not only will new experiments become possible, but previously very difficult experiments will become routine.

Among the new magnet systems we propose for 1996-2000 are both resistive and pulsed magnets that take the maximum field values well beyond what is now available in their respective classes. The 100 T magnet will have a pulse widths of approximately 20 ms for fields above 80 T and 50 ms above 50 T. [7]

Table III — NHMFL Magnets Proposed for Period 1996 - 2000

Power (MW)	Max. Field (T)	Bore Size (mm)	Characteristics	Quantity
24	20	200	Solenoid	1
24	33	32	Solenoid	1
29	36	32	Solenoid	1
40	45	32	Solenoid	1
(1.5 MJ)	80	24	Pulsed field magnet	1
500	100	24	Pulsed, 20-50 ms	1

V. Future Facility Concepts

Looking to the far-term it is possible to see three significant new facilities that will challenge our best efforts (without straining our credulity).

1. 2 GHz NMR.

It was an obvious challenge to consider the question of what the ultimate possibilities of the technical installations would be. The power supply has shown that it is capable of delivering 40 MW with a current quality which is unrivaled in the world. With a few improvements stability and ripple of less than 1 ppm should be attainable. The water cooling circuit was designed and has proven to have uniquely low vibration level. The mass of 3 feet of concrete, on which the magnet cells were constructed, will damp the vibrations of any measuring device to extremely low levels. We are therefore confident that with proper magnet design proton resonance frequencies of 2 GHz in solid state NMR quality will be observable. This was proposed in the Seitz-Richardson panel and would extend the present capabilities by a factor of more than two.

2. 60 T Hybrid magnet.

We are convinced that also the level of continuous fields can be increased considerably. Our calculations show that a hybrid magnet, consisting of a 18 T superconducting magnet with a bore of close to one meter and a 40 MW resistive insert could produce a continuous field of 60 T. The successful design would require a reasonable, but not excessive, development effort for the conductor material of the insert. Improvements of the conductor and of the conduit of the superconducting coil and detailed optimizations of many parameters would also be necessary. It is estimated that a development effort of three years is required. Such a 60 T hybrid magnet would double the available continuous magnetic fields and open completely new possibilities to research in the highest magnetic fields.

3. 100 T long-pulse magnet.

The implicit possibility of a 100 T long-pulse magnet underlies this conference, and we concur with that premise. At NHMFL we are taking specific strides in this direction through the construction of a 60 T quasi-static magnet and the proposed construction of a 100 T, 20 ms magnet in the near term. Both of these are based on our 1.4 GW motor-generator which can be upgraded to give giga-joules of extractable energy with the addition of a flywheel. Design studies of the flywheel and its incorporation in the system have confirmed the feasibility of this upgrade. (The surface of the flywheel will have a speed exceeding Mach 1.) Such a magnet would more than double the field of long-pulse magnets available today.

VI. Re-affirmation of Science Opportunities at 100 T

As mentioned in the Introduction, high magnetic fields are needed by a wide range of disciplines, and strong opportunities for advancing the understanding of specific subjects have been presented in earlier panel reports and in the report of Leuven I. [1,2,9] These remain as relevant today as they were then. Here, we limit ourselves to re-affirming the need for high magnetic fields in a sub-field of condensed matter physics that shows particular promise.

The extensive studies of strongly correlated electronic systems in condensed matter physics in recent years are challenging many of our fundamental concepts. High Tc oxide superconducting materials are a clean example of this, where antiferromagnetism and superconductivity compete on the same energy scale, and where even such simple properties as the temperature dependence of the electrical resistivity have no simple explanation. High magnetic fields can probe directly electron-electron correlations through spin and orbit coupling to the magnetic field. 100 T corresponds to a temperature for the spin system of roughly 80 K, a region where many interesting phenomena occur. We cite a few particular examples where fields of 100 T can be expected to achieve qualitatively new results.

Fermi surface studies in heavy Fermion and layered materials can be extended to find heavier mass sheets, the variation of Fermi surface topology through metamagnetic transitions, as well as direct measurements above Hc2 in cuprates. Critical fields can be cleanly studied in the cuprates and organic materials, and also in the high critical field intermetallics. Additionally, new studies of pinning mechanisms in superconductors will be possible.

Fundamental studies of Kondo insulators can be made in fields comparable to their gap temperatures. New studies of mixed valence materials are also now possible with fields comparable to the fluctuation scale. Serious questions of physics exists for both these classes of materials.

The small ordered-moment magnetic systems can be expected to show new features in 100 T fields, again because such fields permit studies at the ordering temperature scale. In addition, suspected non-Neel ordering in various materials such as UPd3 and URu2Si2 should be sensitive to large applied fields. In these and many of the systems mentioned above, an aim is to be able to separate the various competing energy scales which make the phenomena examined so rich.

Higher fields obviously have great relevance to studies of the fractional quantum Hall effect, with higher fields always leading to new features. The large anisotropies point to Quantum Hall effect possibilities in the organics, and the various analogies between cuprates and organics can be effectively studied in the enlarged dimension attained in high field. New and fundamental studies of important questions in semiconductor physics, such as the nature of DX centers in GaAs, will also be possible.

VII. Opportunities for International Collaboration and Joint Initiatives

As the program of the present conference testifies so well, international collaboration in achieving and using the highest magnetic fields is an established and cherished feature of the world scientific community. There is every prospect that technical and scientific collaboration will be further strengthened as the scale of the facilities increases, and their number correspondingly decrease. In science, the ideas, the challenges, the successes, respect no national barriers.

Perhaps the emerging scale of high field facilities, such as a 100 T long-pulse, quasi-static magnet, will mandate inter-continental funding, as it does for the big-science fields of particle and plasma physics mentioned in the Introduction. It is likely that different national communities will choose different, but complementary, paths to 100 T and the researcher will be able to choose the field, volume, and pulse conditions that best matches his/her experiment. The relevance of high magnetic field research to societal needs, if clearly articulated, should attract national support.

References

1. *High-Magnetic-Field Research and Facilities*, Solid State Sciences Committee, [National Research Council,2101 Constitution Avenue, Washington, D.C. 20418], 1979.

2. *Report of NSF Panel on Large Magnetic Fields*, Division of Materials Research, [National Science Foundation, 4201 Wilson Blvd., Arlington, VA 22230], 1988.

3. *NHMFL - Early Measurements and Science Opportunities*, J. E. Crow, L. J. Campbell, D. M. Parkin, H. J. Schneider-Muntau, and N. Sullivan, Proceedings of RHMF-4, Nijmegen, August 29-31, 1994. (To be published in *Physica* **B**.)

4. *Design, Installation, and Commissioning of the Los Alamos National Laboratory Pulsed Power Generator*, H. J. Boenig, J. B. Schillig, H. E. Konkel, P. L. Klingner, T. L. Peterson and J. D. Rogers, *IEEE Transactions on Energy Conversion* **7**, 260-266 (1992).

5. *Design and Analysis of High-Field Quasi-Continuous Magnets*, L. J. Campbell, H. J. Boenig, D. G. Rickel, J. D. Rogers, J. B. Schillig, J. R. Sims, P. Pernambuco-Wise, H. J. Schneider-Muntau, and L. Van Bockstal, *IEEE Transactions on Magnetics* **30**, 2222 (1994).

6. *Performance Features Preview of the NHMFL 60 Tesla Quasi-Continuous, Controlled Pulse Magnet at Los Alamos*, L. J. Campbell, Los Alamos National Laboratory Report, LA-UR-94-3238.

7. *The U. S. 100 T Project*, L. J. Campbell, Y. Eyssa, P. Gilmore, P. Pernambuco-Wise, D. G. Rickel, J. B. Schillig, and H. J. Schneider-Muntau, Proceedings of RHMF-4, Nijmegen, August 29-31, 1994. (To be published in *Physica* **B**.)

8. *An Overview of the 45 T Hybrid Magnet System for the New National High Magnetic Field Laboratory*, J. R. Miller, M. D. Bird, S. Bole, A. Bonito-Oliva, Y. Eyssa, W. J. Kenney, T. A. Painter, H. J. Schneider-Muntau, L. T. Summers, S. W. Van Sciver, S. Welton, R. J. Wood, J. E. C. Williams, E. Bobrov, Y. Iwasa, M. eupold, V. Stejskal, and R. Weggel, *IEEE Transactions on Magnetics* **30**, 1563 (1994).

9. *Science in 100 Tesla*, European Workshop, Leuven, May 15-17, 1992